Logging and soil disturbance in southeast British Columbia

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Received March 7, 1982[2]
Accepted August 15, 1986

Krag, R., K. Higginbotham, and R. Rothwell. 1986. Logging and soil disturbance in southeast British Columbia. Can. J. For. Res. **16**: 1345–1354.

The purpose of this study was to document and to analyze extent, type, and degree of soil disturbance on ground-skidded and cable-yarded cutovers. The primary hypothesis was that ground skidding on steep, high elevation sites generates more soil disturbance than cable yarding. Thirty-one cutovers were surveyed in the Nelson Forest Region: 25 logged by ground skidding and 6 by cable yarding. Three replications were obtained for each season – slope class on ground-skidded sites. Cable-logged areas were also replicated three times, but only for season. Elevations of the cutovers ranged from 910 to 1970 m with an average of 1360 m. Slope steepness on cutovers ranged from 5 to 74%. Soil disturbance was significantly greater on ground-skidded than on cable-yarded cutovers, averaging 40–45% vs. 22–30%, respectively, regardless of season. Differences in soil disturbance between logging methods by season were small and not significant. Average soil disturbances for summer cable yarding and ground skidding were 30 and 45%, respectively, compared with 22 and 40% for winter operations. Analysis of soil disturbance by source revealed skidroads as the major cause of disturbance on ground-skidded cutovers, regardless of season. The primary source of disturbance on cable-yarded areas was yarding in the summer and haul roads in the winter. Ground skidding also caused more deep to very deep disturbance, averaging 30% in winter and 35% in summer compared with 18 and 14% on cable-yarded sites. For both methods deep and very deep disturbance were most common accounting for 75–80% of total disturbance. Extent of soil disturbance and slope steepness were not significantly related. The high variability in soil disturbance noted in this study was similar to other surveys. Most studies have attempted to associate such variation with major environmental factors but with little success. To fully explain soil disturbance, operational factors such as planning and layout of logging must be considered.

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Le but de cette étude était d'approfondir et d'analyser l'étendue, le type et le degré de perturbation du sol dans des aires de coupe où le débardage était fait avec des câbles et des débusqueuses. On avait préalablement supposé que l'emploi de débusqueuses en terrain élevé et accidenté engendrait plus de perturbation du sol que l'emploi de câbles. Trente-et-une aires de coupes furent inventoriées dans la région forestière de Nelson : 25 débardées avec des débusqueuses et 6 avec des cables. On a obtenu trois répétitions pour chaque classe de saison–pente dans le cas des terrains débardés avec des débusqueuses. Les aires débardées avec des câbles furent aussi répétées 3 fois, mais seulement our sa saison. L'altitude des aires de coupe variait de 910 à 1970 m, avec une moyenne de 1360. La pente des terrains variait de 5 à 74%. La perturbation du sol fut significativement plus grande sur les aires de coupe débardées avec des débusqueuses que sur celles avec des câbles, avec des moyennes de 40–45% et de 22–30% respectivement, quelle que soit la saison. Les différences dans la perturbation du sol entre les procédés d'exploitation suivant les saisons étaient mineures et non significatives. Les perturbations moyennes du sol en été furent de 30% pour le débardage par débusqueuse et de 45% pour celui par câble, par comparaison avec des moyennes de 22 et 40% respectivement durant l'hiver. L'analyse de la perturbation du sol selon la source a indiqué que les chemins de débardage sont la principale cause de perturbation dans les aires débardées avec des débusqueuses, quelle que soit la saison. La cause principale de perturbation dans les aires débardées par câble résidait dans le tracé du câble en été et dans les chemins de halage en hiver. La débusqueuse a aussi provoqué des perturbations plus profondes atteignant 30% en hiver et 35% en été, en comparaison avec 18 et 14% dans les aires débardées par câble. Avec ces deux méthodes, les perturbations profondes et très profondes étaient les plus fréquentes, comptant pour 75 à 80% de toutes les perturbations. L'étendue des perturbations du sol et la déclivité du terrain n'étaient pas reliées de façon significative. La grande variabilité dans la perturbation du sol notée dans cette étude était semblable à celle d'autres inventaires. La plupart des études ont tenté d'associer cette variabilité aux principaux facteurs environnementaux, mais avec peu de succès. Pour expliquer pleinement la perturbation du sol, il faut prendre en considération des facteurs opérationnels comme la planification et le tracé de l'exploitation.

[Traduit par la revue]

Introduction

Soil disturbance and exposure of mineral soil are common consequences of timber harvesting. Soil disturbance can be positive, such as the use of mechanical scarification to prepare cutover sites for seeding or planting. In most cases, however, soil disturbance has negative impacts, resulting in soil erosion, sedimentation, and losses in site productivity (e.g., Ruth 1967; Schwab and Watt 1981). The potential for soil erosion and sedimentation increases as the extent of soil disturbance increases. Tree growth on disturbed sites can also be impaired by compaction or other alterations to the physical and chemical properties of soil (Smith and Wass 1979, 1980). As a result of these environmental impacts, minimization of soil disturbance that is detrimental is often a goal of forest management.

Soil disturbance is frequently used as an index of environmental impacts (Bockheim et al. 1975; Klock 1975; Dyrness 1967), but its value as a predictor of the type, magnitude, and severity of these impacts is not well understood. The processes that link soil disturbance to soil loss and to deterioration of site quality are complex and not easily described by soil disturbance alone. Despite these limitations, soil disturbance is frequently

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[2]Revised manuscript received August 8, 1986.

used to assess environmental impacts of aerial, cable, and ground-skidding logging systems (e.g., Bockheim et al. 1975; Klock 1975; Dyrness 1965, 1967; Ruth 1967; Steinbrenner and Gessel 1955). Comparisons based on total soil disturbed usually without regard to differences in cause or severity of disturbance suggest that ground-skidding methods cause greater impacts than aerial or cable-yarding systems.

Such comparisons, however, leave many important questions unresolved. First, how valid are the results? Many comparisons are based on only a few logged areas and statistical analyses are lacking. Also, physical descriptions and details of logged areas vary in quality, making it difficult to determine whether the sampled areas are representative of average logging conditions and practices for a region.

Secondly, is soil disturbance caused by cable or aerial methods significantly different from that caused by ground skidding? Area of exposure alone does not reflect the severity of disturbance nor does it provide index of soil loss. The processes that contribute to soil disturbance, including felling and road construction, are common to most logging methods, and the properties of disturbed soils with these sources are not likely to vary much between logging systems. Ground skidding differs from cable logging in that it uses tractors or rubber-tired skidders to transport logs from stump to landing. The resultant network of skid trails is an additional source of disturbance not associated with cable or aerial methods. The significance of this extra disturbance is often overlooked, as only a few studies (e.g., Smith and Wass 1976; Dyrness 1965; Steinbrenner and Gessel 1955) have identified or related disturbance to specific sources. To properly assess its importance, therefore, soil disturbance should be analyzed and identified with sources of the disturbance (e.g., landings, haul roads, skid trails, and yarding) and by depth classes rather than as a total.

Finally, how effectively can results from one area be extrapolated to other regions? Soil disturbance information is available for a variety of climatic, topographic, and edaphic settings, but its usefulness is limited by differences in sampling, measurement criteria, and definitions among studies.

This study attempted to respond to some of these problems. The study was done in the Nelson Forest Region of southeastern British Columbia, where a strong controversy existed during the early 1970's over the environmental effects of ground-skidding practices on steep, high-elevation sites. The controversy centred on guidelines developed by the British Columbia Forest Service to encourage a shift from traditional ground-skidding systems to cable-logging systems on high elevation sites, which are susceptible to soil disturbance and erosion.

Objectives

The purposes of this study were to conduct an investigation of ground-skidded and cable-yarded cutovers, and to document and analyze extent, type, and degree of soil disturbance. Specific objectives of the study were (*i*) to determine whether ground-skidding systems generated more soil disturbance than cable-yarding systems; (*ii*) to determine why differences occurred, if any; (*iii*) to compare the severity of disturbance between the two logging systems using depth of disturbance as an index of severity; (*iv*) to examine the effects of slope steepness and season of logging on soil disturbance levels.

Study area description

The study was conducted in the Nelson Forest Region of southeastern British Columbia (Fig. 1), which is mountainous and lies in the Cassiar–Columbia mountains and Eastern System physiographic regions of British Columbia (Farley, 1979). From west to east the Nelson Forest Region consists of four major mountain ranges: the Monashee, Selkirk, and Purcell mountains (all within the Cassiar–Columbia region), and the Rocky Mountains (Holland 1976; Jackson 1976). The Purcells, Selkirks, and Monashees are composed of sedimentary rocks of Proterozoic age with areas of younger metamorphic and igneous rocks, while the younger Rocky Mountains are primarily sedimentary rocks of Paleozoic age (Holland 1976). Relief increases from south to north. Valley bottoms lie at 500–600 m and summits at 2100–2300 m in the south. In the northern part the valley floors are at 600–800 m while the summits are 2500–3500 m in elevation. Climate is strongly influenced by the range in relief and the northwest–southeast orientation of the mountains. Temperatures become cooler and precipitation increases from south to north. Precipitation extremes are particularly pronounced. Mean annual precipitation in the Rocky Mountain Trench ranges from 30–40 cm in the south to 100–150 cm in the north. On the windward slopes of the Monashees and Selkirks annual precipitation is 40–50 cm in the south and 150–250 cm or more in the north. Snowfall also increases from south to north and is heaviest in the northwestern part of the Nelson Forest Region (Farley 1979).

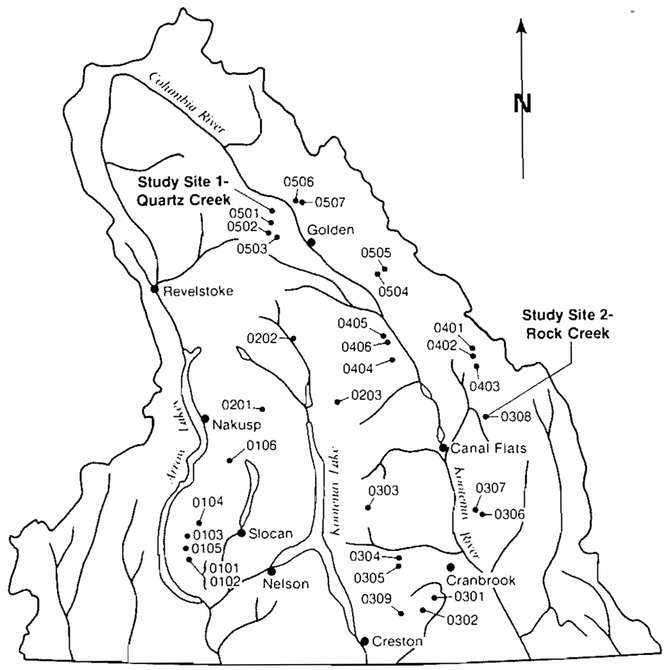

FIG. 1. Locations of clear-cuts surveyed for soil disturbance and skid road characteristics, Nelson Forest Region, British Columbia.

Study methods

Soil disturbance was evaluated on clear-cuts logged by cable and ground-skidding methods for winter and summer conditions on gentle to steep slopes (i.e., 0 to > 40%). Ground skidding consisted of the removal of felled trees by rubber-tired skidders or crawler tractors. Cable methods studied were high lead and grapple-yarding systems (Wellburn 1975; Lyson 1974; Studier and Binkley 1974). Winter conditions were defined as logging on snow and (or) frozen ground. Summer conditions were defined as logging on snow-free and unfrozen ground. All cut blocks were 4 years old or less and had experienced no postharvest treatments that would have altered the character and (or) extent of soil disturbance. Where possible, high-elevations sites (above 1200 m) were selected for study. Ground-skidded sites were stratified into three slope classes: less than 20%, 20–40%, and >40%. Cable-logged sites were not stratified by slope as there were not enough suitable sites available.

Soil disturbance was surveyed on the cut blocks by methods and procedures developed by Smith and Wass (1976). Exposed mineral soil was selected as an index of soil disturbance (Bockheim et al. 1975; Smith and Wass 1976). Point samples (Smith and Wass 1976) were established on transects angled across contours in cut blocks to intersect haul roads and skid roads. Transects were aligned in a zigzag pattern across cut blocks to achieve the desired sampling intensity. Sample points were established at 2-m intervals with 15–20 points/ha as a goal. A minimum of 400, and preferably between 700 and 900 points was sampled on each clear-cut.

Sample points were characterized as "disturbed" (mineral soil exposed), "undisturbed" (mineral soil not exposed), or "other" (nonsoil area) (Smith and Wass 1976). Disturbed points were identified by depth (light, 0–5 cm; deep, 5–25 cm; very deep, >25 cm), source (haul road, skid road, landing, yarding, or skidding), and location whether on haul roads, skid roads, or landings (sidecast, road surface, or cutbank). "Other" included stumps, windfalls, logging slash >5 cm in diameter, and rocks >25 cm in diameter. A point classed as "other" but located on a disturbed surface (e.g., a piece of slash on a landing) was further identified by its location. A point sample that did not fall on exposed mineral soil or meet the criteria of the "other" category was classed as "undisturbed." This included points where duff was disturbed but mineral soil was not exposed. Intimate mixtures of duff and mineral soil were classed as "light" soil disturbance. Soil disturbance in total or for specific sources or depth classes was expressed as a percentage by the following:

$$\% \text{ disturbance} = (\text{no. disturbed sample points}) / (\text{total no. of points}) \times 100$$

Data analysis

Soil disturbance data were analyzed by two analysis of variance tests. Each analysis was a four-way classification of the data and employed a randomized block design with uneven subgroups. The basic measurement used in the analyses was percent disturbance by depth class. The bulk of survey data fell outside of the 30–70% range, so it was necessary to normalize the data by applying an arcsine percentage transformation (Zalik 1976).

Analysis I compared cable-yarded cut blocks with ground-skidded cut blocks. The analysis was restricted to clear-cuts having average slopes steeper than 20% to reduce the disparity in terrain conditions between the two logging systems. The data were grouped by source of disturbance, season of logging, and logging system. Analysis II compared soil disturbance between summer and winter ground-skidded cut blocks. The data were grouped and tested for differences and interactions between season, slope class, source of disturbance, and depth of disturbance. Means for all statistically significant main effects and interactions were compared using the Newman–Keuls range test (Hicks 1973).

Results

Thirty-one clear-cut blocks were surveyed. Twenty-five were logged by ground-skidding and 6 by cable methods. At least three replications were obtained for each season–slope class for ground-skidded sites. Cable-logged sites were also replicated three times, but only for season. Ground-skidded sites, winter and summer, were more plentiful than cable-logged areas, reflecting their importance as the dominant logging method in the Nelson Forest Region (Wellburn 1975). Locations of sampled cut blocks are shown in Fig. 1. Elevations of the clear-cuts ranged from 910 to 1970 m, with an average elevation of 1360 m. Average elevations for summer- and winter-logged ground-skidded blocks were, respectively, 1390 and 1360 m. Average elevations for summer and winter cable-logged areas were 1200 and 1400 m, respectively. Forest types sampled included Englemann spruce/subalpine fir, interior Douglas-fir, and interior western hemlock (Pojar 1983). Average slopes for all clear-cuts ranged from 5.2 to 74.2%. Slopes on winter and summer grounded-skidded sites were similar, averaging 27 and 30%, respectively. The slopes on cable-logged areas for winter and summer operations were higher, averaging 41 and 62%, respectively.

A summary of observations (Table 1) on all cut blocks revealed 16 to 18% more soil disturbance caused by ground-skidding than by cable-logging. Soil disturbance for ground skidding and cable logging was, respectively, 40 to 45 and 22 to 30%. Consideration of season of logging revealed 5 to 7% less soil disturbance caused by winter operations than summer operations. Average soil disturbance for summer ground-skidding and cable-logging was 30 to 45% compared with 22 to 40% for winter operations. Analysis of variance indicated differences in soil disturbance between logging methods were significant, while those between season were not significant (Table 2).

Analysis of soil disturbance by source revealed similar patterns for winter and sumer ground-skidding operations (Fig. 2), but very different patterns for winter and summer cable-logging operations. The primary source of soil disturbance on ground-skidded areas regardless of season was skid roads, averaging 24 to 29%, followed by haul roads at 7 to 8%, landings at 4 to 5%, and skidding at 3 to 4%. The primary source of disturbance on summer cable-logged areas was yarding, averaging 16%. Haul roads, skid roads, and landings averaged 9, 3, and 1%, respectively. In contrast, the primary source of disturbance on winter cable-logged areas was haul roads, averaging 17%. Yarding, skid roads, and landings averaged 3, 3, and 0.5%, respectively. Skid roads occurring on cable-logged areas were infrequent and only used to reach small areas inaccessible to the cable yarder. Analysis of variance (Table 2) indicated differences in soil disturbance between the different sources were significant.

Soil disturbance summarized by depth classes revealed ground skidding caused more deep and very deep soil disturbance than cable yarding (Fig. 3). Deep and very deep disturbance classes on summer and winter ground-skidded sites ranged from 14 to 19% compared with 4 to 14% for cable-logged sites. Light soil disturbance ranged from 4 to 11% on summer and winter ground skidding, and winter cable logging, but was 15% on summer cable logging. In general deep and very deep disturbance were most common, regardless of logging method or season, accounting for 74 to 81% of total soil disturbance. The only exception was summer cable logging, where disturbance was evenly divided between the deep and very deep classes and the light class. Analysis of variance indicated that differences in soil disturbance between the depth classes were significant (Table 2).

Analysis of depth of disturbance also revealed significant differences and interactions between methods, depths, sources, and seasons (Table 2). Each disturbance source showed a clear and consistent pattern that was independent of method and season of logging (Table 3). Haul roads on both cable and skidding operations were characterized predominantly by very deep disturbance, with 67 to 80% of all haul road disturbance classed as very deep. Landing related disturbance showed a pattern similar to haul roads but was much less in magnitude, averaging between 0 and 3%, with very deep disturbance accounting for 56 to 69% of total disturbance. Depth of disturbance for skid roads with both methods of logging was similar, with deep disturbance dominant, followed by very deep and light disturbance. The magnitudes of deep disturbance, however, were different, and ranged from 12 to 13% on ground-skidded areas compared with 1.4 to 1.5% on cable-logged sites.

TABLE 1. Summary of percent soil disturbance on surveyed cable-logged and ground-skidded cut blocks, Nelson Forest Region, British Columbia

Block No.	Block location	Source of disturbance: Haul roads	Landings	Skid roads	Yarding or skidding	Total soil disturbance
		Cable logging, summer				
0103	Brodie Cr.	9.5%	0.0%	0.5%	11.5%	21.5%
0309	Kid Cr.	8.5	2.3	1.5	14.8	27.1
0404	Campbell Cr.	9.1	1.6	6.4	22.8	39.9
Averages		9.0	1.3	2.8	16.4	29.5
		Cable logging, winter				
0102	Grizzly Cr.	16.6	0.0	6.4	3.2	26.2
0106	Shannon Cr.	9.7	0.0	1.7	0.9	12.3
0301	Lamb Cr.	23.5	1.4	0.0	3.5	28.4
Averages		16.6	0.5	2.7	2.5	22.3
		Ground skidding, summer				
0101	Grizzly Cr.	12.1	1.5	11.0	4.2	28.8
0201	Poplar Cr.	4.9	0.3	27.2	1.6	34.0
0302	Lamb Cr.	0.7	1.5	24.0	3.7	29.9
0303	Dewar Cr.	3.9	4.3	32.0	3.4	43.6
0304	Hellroaring Cr.	12.0	11.9	38.1	1.9	63.9
0308	Rock Cr.	5.6	0.1	37.4	4.4	47.5
0403	Lower Palliser R.	6.1	6.0	12.9	5.6	30.6
0503	Quartz Cr.	9.5	18.0	36.4	1.1	65.0
0506	Copper Cr.	10.8	5.0	33.3	1.3	50.4
0507	Copper Cr.	17.3	2.5	36.0	4.9	60.7
Averages		8.3	5.1	28.8	3.2	45.4
		Ground skidding, winter				
0104	Hoder Cr.	6.6	0.0	22.9	3.6	33.1
0105	Grizzly Cr.	11.3	0.0	33.9	5.5	50.7
0202	Duncan R.	11.3	1.2	26.9	10.7	50.1
0203	Glacier R.	12.0	0.0	15.4	3.2	30.6
0305	Hellroaring Cr.	8.3	8.3	32.0	2.5	51.1
0306	Nicol Cr.	10.3	6.3	34.7	0.9	52.2
0307	Nicol Cr.	9.4	0.9	31.7	2.6	44.6
0401	Lower Palliser R.	8.1	11.1	10.9	13.9	44.0
0402	Lower Palliser R.	10.3	4.5	37.3	0.3	52.6
0405	Hall Lakes	2.8	9.2	6.3	7.3	25.6
0406	Hall Lakes	4.0	3.5	2.3	3.9	13.7
0501	Quartz Cr.	7.2	8.0	23.1	2.3	40.6
0502	Quartz Cr.	1.0	3.6	30.0	0.3	34.9
0504	Dainard Cr.	10.1	4.9	28.9	1.9	45.8
0505	Dainard Cr.	1.9	3.4	30.2	1.0	36.5
Averages		7.6	4.3	24.4	4.0	40.4

Disturbance patterns associated with yarding and skidding were similar for each method and both seasons. Light disturbance was predominant and ranged from 2 to 14% and accounted for 72 to 92% of total disturbance, with deep disturbance making up most of the remainder. The patterns of disturbance for methods and seasons were similar, with no large differences between or within these stratifications. For both methods and seasons, deep disturbance and very deep disturbance were most common accounting for more than 75% of total disturbance.

Analysis of soil disturbance stratified by season, sources, slope, and depth for ground skidding alone indicated significant differences between source and depth of disturbance and no significant differences between season and slope (Table 4). Overall disturbance on summer ground-skidded areas varied from 41 to 47% compared with 34 to 45% on winter ground-skidded sites (Table 5). Soil disturbance showed a weak trend of increasing with slope. However, when soil disturbance was arranged by slope classes only small differences of 1 to 2% were evident between slope classes and within and between seasons.

The relationships between severity of soil disturbance and slope steepness were variable (Table 5). Deep and very deep disturbance for both seasons generally showed an increasing trend from gentle to steep slopes. The trend for very deep disturbance alone was significant at the 5% level. In general, deep and very deep depth classes accounted for the greatest amount of disturbance, averaging 13–26 or 56–84% of total

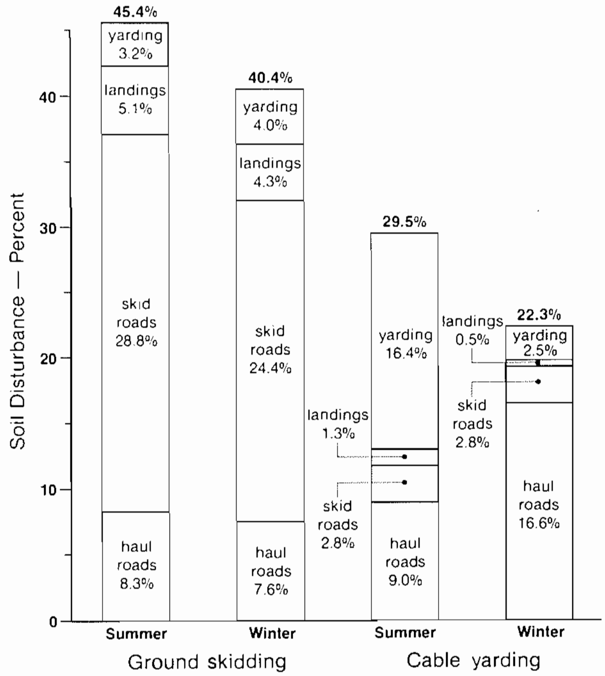

FIG. 2. Contribution by source to average total soil disturbance for summer and winter logged ground-skidded and cable-yarded cut blocks, Nelson Forest Region, British Columbia.

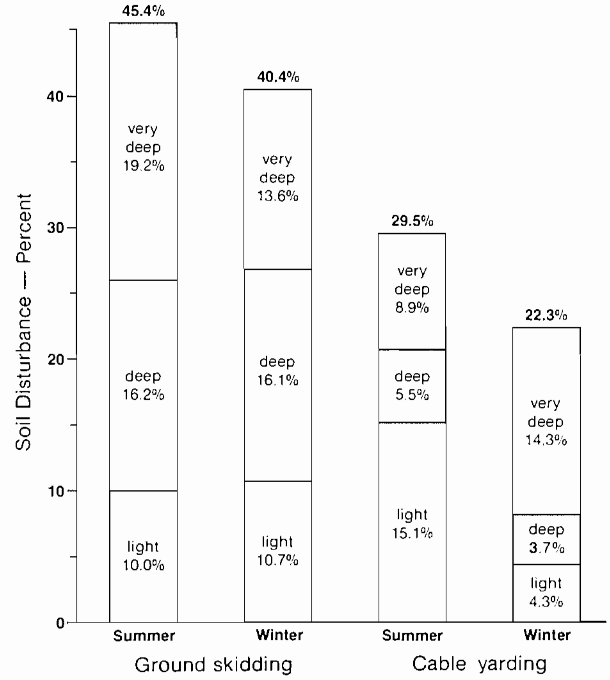

FIG. 3. Distribution of average total soil disturbance by depth class, all sources, for summer and winter logged ground-skidded and cable-yarded cut blocks, Nelson Forest Region, British Columbia.

TABLE 2. Analysis of variance of cable logging versus ground skidding on slopes >20% stratified by method, season of logging, source of disturbance, and depth of disturbance, Nelson Forest Region, British Columbia

Source of variation	df	MS	*F*
Main effects			
Method of logging (M)	1	380.45	32.91*
Season of logging (Se)	1	5.88	0.51
Source of disturbance (Sd)	3	1 450.55	125.48*
Depth of disturbance (De)	2	173.23	14.99*
Interactions			
Method × Season (M × Se)	1	38.16	3.30
Method × Source (M × Sd)	3	734.25	63.52*
Method × Depth (M × De)	2	66.24	5.73*
Season × Source (Se × Sd)	3	58.49	5.06*
Season × Depth (Se × De)	2	14.18	1.23
Source × Depth (Sd × De)	6	462.21	39.98*
M × Se × Sd	3	22.67	1.96
M × Se × De	2	13.47	1.17
M × Sd × De	6	23.11	2.00
Se × Sd × De	6	21.81	1.89
M × Se × Sd × De	6	9.81	0.85
Error	216	11.56	
Total	263		

*Significant at the 95% level.

disturbance. Winter ground-skidding on slopes less than 20% was the only exception. Very deep disturbance on these lower slopes averaged only 6%, while light disturbance was 15 or 45% of total disturbance in this slope class.

The results for soil disturbance by source on ground-skidded sites were similar to those in the earlier analysis. Maximum

TABLE 3. Distribution of average soil disturbance (%) by source and depth class on cable-yarded and ground-skidded cut blocks for summer and winter, Nelson Forest Region, British Columbia

Logging method, logging season, and source of disturbance	Depth class: Light	Deep	Very deep	Total disturbance by source
Ground skidding, summer				
Haul roads	0.5	1.3	6.5	8.3
Skid roads	6.9	12.6	9.3	28.8
Landings	0.3	1.5	3.3	5.1
Logging	2.3	0.7	0.2	3.2
Totals by depth class	10.0	16.2	19.2	45.4
Ground skidding, winter				
Haul roads	0.6	1.9	5.1	7.6
Skid roads	6.5	12.0	6.0	24.4
Landings	0.5	1.5	2.4	4.3
Logging	3.1	0.7	0.1	4.0
Totals by depth class	19.7	16.1	13.6	40.4
Cable yarding, summer				
Haul roads	0.9	1.4	6.7	9.0
Skid roads	0.2	1.4	1.2	2.8
Landings	0.3	0.1	0.9	1.3
Logging	13.7	2.6	0.1	16.4
Totals by depth class	15.1	5.5	8.9	29.5
Cable yarding, winter				
Haul roads	1.4	1.9	13.3	16.6
Skid roads	0.6	1.5	0.7	2.8
Landings	0.0	0.2	0.3	0.5
Logging	2.3	0.2	0.0	2.5
Totals by depth class	4.3	3.7	14.3	22.3

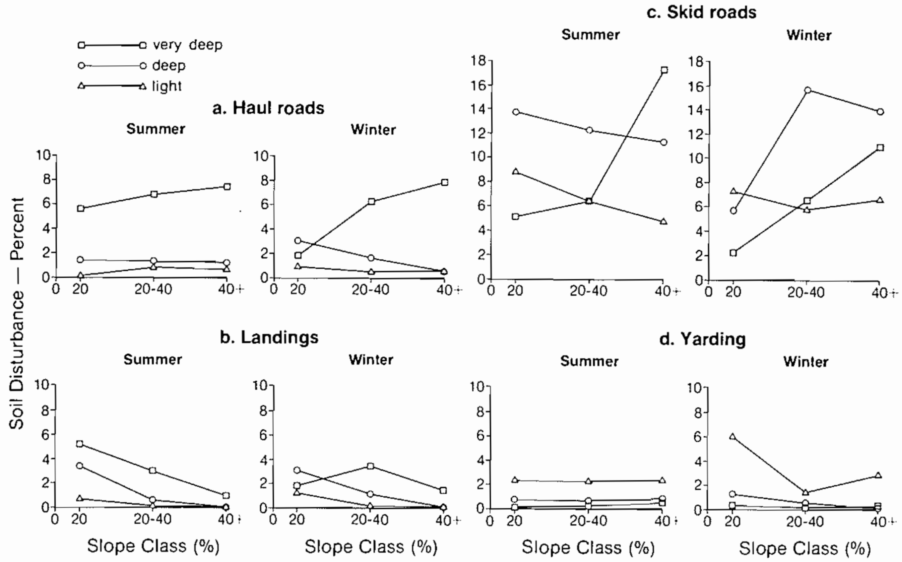

FIG. 4. Trends in light, deep, and very deep soil disturbance by source with increasing slope on summer and winter ground-skidded sites: (*a*) haul roads, (*b*) landings, (*c*) skid roads, (*d*) yarding.

TABLE 4. Analysis of variance of summer versus winter ground skidding on cut blocks with slopes of 0 to 40% by season, slope, source of disturbance, and depth of disturbance, Nelson Forest Region, British Columbia

Source of variation	df	MS	*F*
Main effects			
Season of logging (Se)	1	18.99	1.23
Slope class (Sl)	2	0.59	0.04
Source of disturbance (Sd)	3	2 103.01	136.29*
Depth of disturbance (De)	2	105.52	6.84*
Interactions			
Season × slope (Se × Sl)	2	7.22	0.47
Season × source (Se × Sd)	3	11.77	0.76
Season × depth (Se × De)	2	20.48	1.33
Slope × source (Sl × Sd)	6	125.37	8.13*
Slope × depth (Sl × De)	4	109.68	7.11*
Source × depth (Sd × De)	6	388.41	25.17*
Se × Sl × Sd	6	32.34	2.10
Se × Sl × De	4	20.64	1.34
Se × Sd × De	6	4.12	0.27
Sl × Sd × De	12	30.20	1.96*
Se × Sl × Sd × De	12	10.98	0.71
Error	228	15.43	
Total	299		

*Significant at the 95% level.

TABLE 5. Distribution of average soil disturbance (%) by slope and depth class for summer and winter ground-skidded cut blocks, Nelson Forest Region, British Columbia

Season of logging and slope class	Depth class			Total soil disturbance
	Light	Deep	Very deep	
Summer				
<20%	12.0	19.3	16.1	47.4%
20–40%	9.6	14.8	16.6	41.0
>40%	7.7	13.4	26.2	47.4
Winter				
<20%	15.3%	13.1%	5.8%	34.2%
20–40%	7.8	18.8	16.3	42.9
>40%	10.1	14.6	20.6	45.3

disturbance was from skid roads and varied from 28 to 34 and 15 to 31% for gentle to steep slopes for summer and winter operations, respectively. Skid road disturbance increased as slope steepness increased, especially for winter logging (Fig. 4). Analysis showed skid road disturbance was significantly greater on moderate to steep slopes (i.e., >20%) than on gentle slopes. Disturbance from landings decreased from 6 to 1% for very deep disturbance with increasing slope. Landing-related disturbance was found to be significantly greater on gentle slopes than on moderate to steep slopes (Fig. 4).

Further examination of depth of disturbance for ground skidding revealed significant interactions between depth of disturbance, source, and slope classes. Haul roads showed a weak, increasing trend for very deep disturbance with slope (Fig. 4). Very deep soil disturbance ranged from 2 to 8%. Deep and light disturbance classes on haul roads did not show any trends with slope. This pattern was the same for both winter and summer operations. Depth of disturbance for skid roads for winter and summer was different. Summer operations revealed decreasing disturbance with slope for deep disturbance and light disturbance (14 to 10 and 9 to 5%, respectively) and an increasing trend (5 to 18%) for very deep disturbance. Winter operations in contrast showed increasing deep and very deep disturbance with slope, while light disturbance showed no trend with slope. Deep and very deep disturbance classes varied from 5 to 14% and 2 to 10%, respectively. Patterns of depth of disturbance for landings and yarding or skidding for both seasons were similar, averaging 1 to 3%, with a slightly negative to zero relationship for all depth classes and slopes.

Discussion

This study showed summer and winter ground skidding generated 1.5 and 1.8 times more soil disturbance, respectively, than cable logging in corresponding seasons. Soil disturbance

TABLE 6. Comparison of mineral soil exposure (%) generated by ground-skidding, cable, and aerial logging systems in British Columbia and the northwestern United States

Investigators and region	Ground skidding: Horse	Ground skidding: Tractors	Cable systems: Jammer	Cable systems: High lead	Cable systems: Grapple	Cable systems: Skyline	Aerial systems: Balloon	Aerial systems: Helicopter	Comments
Fowells and Schubert 1951, N California	—	22(s)	—	—	—	—	—	—	—
Garrison and Rummel 1951, E Oregon, Washington	12	21(s)	15	—	—	—	—	—	—
Steinbrenner and Gessel 1955, SW Washington	—	26(s)	—	—	—	—	—	—	Includes only skid roads
Dryness 1965, 1967, 1972, SW Oregon	—	35(s)	—	31(s)	—	12(s)	6(s)	—	—
Ruth 1967, W Oregon	—	—	—	16	—	6	—	—	—
Bockheim et al. 1975, SW British Columbia	—	69(s)	—	29	—	—	—	5%	Does not include haul roads and landings
Hetherington 1976, S central British Columbia	—	20(w)	—	—	—	—	—	—	—
Klock 1975, N central Washington	—	74(s)	—	76	—	25	—	12	Area was salvage logged after wildfire
Clayton 1981, central Idaho	—	—	—	—	—	—	—	5	—
Utizig and Herring 1975, S coastal and SE British Columbia	—	16	—	5	—	—	—	—	Recorded only disturbance deeper than 25 cm (very deep)
Smith and Wass 1976, SE British Columbia	—	46(s) 29(w)	13(s)	17(s) 17(w)	29(s) 22(w)	8(s)	—	—	—
Hammond 1978, SW British Columbia	—	28(s) 39(w)	—	—	—	—	—	—	Does not include off-road (yarding) disturbance
Schwab and Watt 1981, central British Columbia	—	45(s) 49(w)	—	—	12	—	—	—	Does not include haul roads and landings
Current study, SE British Columbia	—	45(s) 40(w)	—	31(s) 26(w)	27(s) 20(w)	—	—	—	—

NOTE: s, summer; w, winter.

averaged 45 and 40% on summer and winter ground-skidded sites, compared with 30 and 22% on summer and winter cable-logged sites. In general, observed soil disturbance was similar to values reported by others (Table 6), with cable and ground-skidding disturbance falling in the middle to upper range of reported values in the literature. There was good agreement with three earlier studies done in interior British Columbia (Smith and Wass 1976; Hammond 1978; Schwab and Watt 1981). Disturbance in these studies for summer and winter tractor logging averaged 46 and 29, 28 and 39, and 45 and 49%, respectively. Disturbance from high-lead logging in this study, however, was greater than reported by Smith and Wass (1976) but was similar for grapple logging.

This study also agreed with previous work that tractor logging causes more soil disturbance than cable or aerial methods. Less disturbance on cable-logged areas was in part due to less skid road development in the cut blocks. Disturbance from skid roads and haul roads combined on cable-logged sites was 12–19% compared with 32–37% on ground-skidded sites.

Cable and aerial logging systems should produce the least amount of disturbance because of reduced overall road densities. In theory, if all environmental and other logging factors were equal, total soil disturbance on cable-logged cut blocks should decrease as yarding distance and road spacing increase. Based on this assumption, jammer systems, with the shortest average yarding distance, should generate the highest levels of disturbance, followed by grapple yarding, high-lead and skyline systems. Examination of Table 6, however, shows greater disturbance with high lead systems than with jammer systems. Factors making it difficult to rank these logging systems are

TABLE 7. Comparison of selected studies giving soil disturbances as a percent of logged area by source

	Source of disturbance			
	Haul roads	Landings	Skid roads	Yarding
		Ground skidding		
Hammond 1978				
Summer	3.0	3.8	20.7	—
	(0.0–7.7)[a]	(0.0–7.0)	(8.6–28.8)	—
Winter	7.6	9.5	21.3	—
	(1.6–16.1)	(2.4–15.5)	(14.8–29.9)	—
Schwab and Watt 1981				
Summer	—	—	38.1	6.6
	—	—	(28.2–51.2)	(1.7–13.4)
Winter	—	—	40.4	8.2
	—	—	(30.0–48.1)	(3.8–13.7)
Smith and Wass 1976				
Summer	7.6	0.7	31.6	3.6
	—	—	—	—
Winter	2.9	0.6	17.8	4.7
	—	—	—	—
Current study				
Summer	8.3	5.1	28.8	3.2
	(0.7–17.3)	(0.1–18.0)	(11.0–38.1)	(1.1–5.6)
Winter	7.6	4.3	24.4	4.0
	(1.0–12.0)	(0.0–11.1)	(2.3–37.3)	(0.3–13.9)
		Cable systems		
Hammond 1978	—	—	—	—
Schwab and Watt 1981				
Summer and winter	—	—	0.0	11.6
	—	—	(0.0)	(8.8–17.4)
Smith and Wass 1976[b]				
Summer	3.8	0.7	9.9[c]	3.5
	—	—	—	—
Winter	2.5	0.0	16.6[c]	1.8
Current study				
Summer	9.0	1.3	2.8	16.4
	(8.5–9.5)	(0.0–2.3)	(0.5–6.4)	(11.5–22.8)
Winter	16.6	0.5	2.7	2.5
	(9.7–23.5)	(0.0–1.4)	(0.0–6.4)	(0.9–3.5)

[a]Ranges are in parentheses.
[b]Summer data include high-lead, grapple, and jammer yarding; winter data include high-lead and grapple yarding.
[c]Includes tail-hold roads and miscellaneous cat roads.

specific site conditions, which confound comparisons, geographic locations with associated differences in climate and forest types, and small sample sizes. Consequently, the base of information is too limited to develop a valid ranking of cable systems.

Surprisingly, season of logging had no effect on soil disturbance levels. Differences between seasons were small, with winter soil disturbance 5 to 7% less than summer disturbance. Smith and Wass (1976) also observed less disturbance on winter ground-skidded sites, but Hammond (1978) and Schwab and Watt (1981) reported the opposite. Therefore if seasonal differences exist, they may not be represented by the index of total mineral soil exposure. Detection also may be limited by sample size, confounded by variability between sample sites, or differences in depth or snow or depth of soil freezing. For example, high values of yarding disturbance on summer cable-logged sites were attributed to poor deflection over uniform steep slopes and to thin litter and duff layers on dry, southerly exposures. In comparison, yarding disturbance was less on winter cable-logged sites as a result of gentle slopes, deep duff layers, and the presence of protective snow packs.

Slope steepness had a stronger effect than season of logging on soil disturbance. The data suggested that disturbance increased in both extent and depth with increasing slope. Deep and very deep disturbance increased with slope, while light disturbance showed no trend with slope. There were only two specific differences found to be statistically significant: (*i*) skid road related disturbance was greater on slopes >20% than on slopes <20%, and (*ii*) landing-related disturbance was greater on slopes <40% than on slopes >40%. These findings generally agreed with Smith and Wass (1976), who reported skid road disturbance was twice as high on slopes steeper than 60% than on gentler slopes for winter logging but not for summer logging. Garrison and Rummel (1951) also found soil disturbance was 2.8 times greater on slopes >40% than on lesser slopes.

Source and depth of disturbance were considered better indices for explaining logging system – soil disturbance relationships than total soil disturbance. For example, most of the disturbance on ground-skidded sites was caused by skid roads, which disturbed 29% of summer and 24% of winter ground-skidded blocks, but which disturbed only 3% of all cable yarded areas. In contrast the two logging systems were similar in terms of haul road and landing requirements, with disturbance for ground skidding and cable logging varying from 11 to 13 and 10 to 17%, respectively.

Soil disturbance characterized by source compared favorably to values reported by others in the region (Table 7). Average values for disturbance differed between the studies, but the ranges were reasonably consistent. Skid roads accounted for more than one-half of total soil disturbance on most ground-skidded cut blocks. Haul roads were generally the second largest source of disturbance for both logging methods. Smith and Wass (1976) reported less average haul road, landing, and yarding disturbance but more skid road disturbance than this study. However, Smith and Wass combined tail-hold roads on grapple-yarded cut blocks with skid roads, while in this study tail-hold roads were not present.

Patterns of soil disturbance by depth were best explained by examining relationships between source and depth of disturbance. The high level of very deep disturbance on winter cable-yarded sites was directly linked to high haul road density, since haul roads were characterized by a high proportion of very deep disturbance. Similarly, the high level of light disturbance on summer cable-yarded sites corresponded to high levels of yarding disturbance, most of which was classed as light. More important, it was observed that ground skidding caused significantly more deep and very deep disturbance than cable yarding. This was attributed to skid roads and their contribution to the deep and very deep depth classes.

The patterns of depth disturbance in this study compared favorably with those of Smith and Wass (1976). Both studies showed that haul roads and landings primarily generated very deep disturbance and that yarding disturbance was characteristically shallow. Smith and Wass found skid roads generated mostly very deep (>25 cm) disturbance, where this study indicated skid road disturbance was mostly deep (5–25 cm). This difference can be attributed to slope differences of cut blocks in the two studies. Average slope steepness in the Smith and Wass study was 58%, while in this study it was only 33%.

Implications for forest managers from this study are similar to those expressed by Smith and Wass (1976): until more information is gained, mineral soil exposure should be assumed to result in an increase in erosion and disturbance deeper than 25 cm should be considered to be potentially harmful to a site. Furthermore, some maximum permissible extent and severity of soil disturbance on steep slopes should be considered. Such limits will vary with site, but even on stable soils, exposure in excess of 25 to 30% on steep slopes should be avoided.

Depth of disturbance is widely considered synonymous with severity of disturbance. However, disturbance to the upper few centimetres can be beneficial as a silvicultural prescription for seedbeds. Deep disturbance appears to have limited value, especially on steep mountain slopes where the rooting zone is often shallow and subsoils are compacted, unweathered, and relatively infertile. Since very deep disturbance appears most harmful, forest managers should plan to control and reduce its extent and to rehabilitate severely disturbed sites after logging.

Some options for reducing soil disturbance include use of alternative logging systems and modification of existing systems. The use of cable or aerial systems in place of ground skidding should potentially reduce soil disturbance as skid roads are not required. However, to gain this advantage cable systems must be carefully planned and implemented, especially on steep slopes where disturbance can be severe. Furthermore, except for skid roads the sources of disturbance are similar for both systems, and cable systems are very expensive. Wellburn (1975) estimated total logging costs per unit for skidders, tractors, and a variety of alternative cable systems and determined that skidders were the least expensive ($6.25/Ccf), tractors next least expensive ($9.03/Ccf), and cable the most expensive ($9.93–12.91/Ccf). Lack of data on long-term effects of site disturbance precludes determining whether reductions in loss of productivity of sites will offset the higher costs of cable logging.

Modification of existing logging systems may be a better alternative to reducing soil disturbance. Modifications include measures such as improved planning and supervision of operations, and use of different ground-skidding machines. Evaluation of preplanning of skid road networks by Froehlich et al. (1981) demonstrated skid trail disturbance was reduced by 45–65% from unplanned operations. The use of smaller machinery can result in less soil disturbance in some situations. McMorland (1980) reported the use of small crawler tractors (e.g., equivalent to Caterpillar D-4) in place of conventional sized tractors (e.g., D-6 size) in the Nelson Forest Region reduced total soil disturbance by one-third as a result of skid roads with smaller dimensions than those necessitated by larger machinery.

In summary, this study and most other soil disturbance surveys are characterized by high variability in disturbance estimates, especially for ground-skidding systems. This also applies between studies. Most studies have attributed some of the variation to major environmental influences, such as season of logging or slope steepness, but with inconclusive results. Researchers have not considered factors relating to the logging operation itself, such as its layout and organization, skidding patterns and methods, type and size of equipment, tree size and volume, and the logging crew itself. The effects of these factors on soil disturbance are unknown at this time. It seems probable that future studies will have to consider some of these operational factors if reasons for the high variation are to be understood.

Acknowledgment

Support for this study from the Forest Engineering Research Institute of Canada, Vancouver, is gratefully acknowledged.

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